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Abstract

As part of a recent NCCARF funded project "Approaches to Risk Assessment on Australian Coasts", a modelling framework was developed which integrated geological, engineering and economic approaches for assessing the risk of climate change along the Australian Coast. This paper aims to demonstrate the working of the framework in deriving probabilistic coastal hazard lines. Within the framework, means for combining results from models that focus on the decadal to century time scale (geomorphic), and those that focus on the short term and seasonal time scales (storm bite and recovery) have been developed. This combination is necessary for the derivation of probabilistic hazard lines. The Narrabeen - Collaroy embayment on the northern beaches of Sydney was chosen as an appropriate study site due to its data rich nature, with directional wave records extending back 20 years, and ongoing repeated beach survey available since the mid 1970's. The site has been subject to extensive study over recent decades. To demonstrate operation of the framework two models with stochastic capabilities were adapted for use in the study. These are the Shoreface Translation Model (STM), for century scale geomorphic evolution, and the Joint Probability Method - Probabilistic Coastline Recession (JPM-PCR) for shorter term beach erosion and recovery. Both models are introduced and discussed. When projecting forward to future scenarios involving sea level rise, the framework also enables sea level rise over time to be input as a probabilistic variable. Recent research has also provided some guidance as to how this can be achieved using outputs from the most recent IPCC estimates. Overall, the research efforts have aimed to point a way forward that enables the quantitative assessment of coastal hazard likelihood for use in robust coastal risk assessment. This contrasts with present practice which typically adopts a more qualitative approach to risk assessment.

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Probabilistic Coastal Hazard Lines for Risk Based Coastal Assessment

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Keywords: coastal hazard, probabilistic modelling.

1. Introduction

This paper aims to introduce and demonstrate a coastal hazard risk framework that has been developed as part of the NCCARF funded project *Approaches to risk management on Australian Coasts: A model framework for assessing risk and adaptation to climate change on Australian Coasts*.

Through necessity, this paper can only provide a brief summary of the study outcomes. The full study findings are contained in [23]. This paper briefly discusses different aspects of the framework with demonstration by application to our primary study site, the Narrabeen/Collaroy embayment on the northern beaches of Sydney.

2. Framework Overview

A risk management approach to coastal hazards is becoming more common. For example, the present guidelines for Coastal Zone Management Plans in New South Wales [6] advocate a risk management approach. The present standard for formal risk management is contained in ISO 31000 [22], which builds from the previous standard AS/NZS 4360:2004.
The approach promoted by these standards is shown in **Figure 1**.

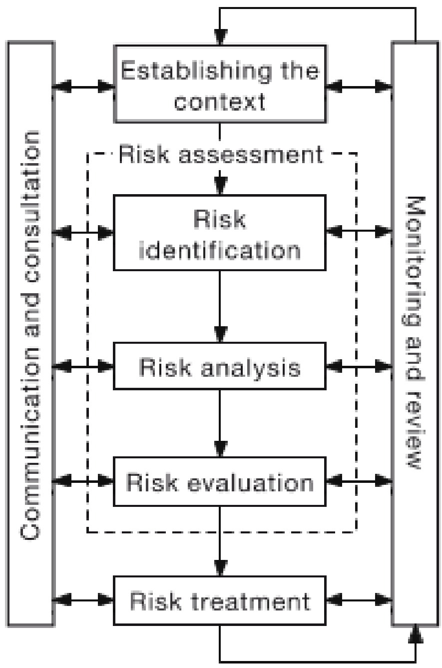

Figure 1: The Risk Management Approach from ISO 31000. Herein we are discussing the "risk assessment" phase. The subject framework focusses on using models to quantitatively assess risks.

The formal standard is flexible, allowing for the incorporation of uncertainty in a transparent manner. This is of benefit when balancing quantitative estimates of uncertain coastal hazards against, for example, the intangible values inherent in coastal land. Even without full probabilistic analysis of risks, successful risk assessment can be undertaken [19, 20].

In condensed form, the coastal hazard *risk analysis* process comprises (i) determination of the extent or severity of identified hazards for a range of exceedance levels (i.e. the *probabilities*); and (ii) determination of the value lost for the extents and/or severities identified in (i) (i.e. the *consequences*). By quantifying both of these, the overall cost of risk can then be calculated by multiplying the probability density function of hazard severity by the corresponding curve of cumulative damage value vs. hazard severity. Herein we focus on hazards associated with the movement of a dune scarp on a sandy beach.

That process becomes more complicated when it is applied to planning over long time frames with non-stationary boundary conditions, such as the expected sea-level rise over the next century [11, 23].

However, the quantitative probabilistic assessment of coastal hazards is a precursor to these more complicated assessments. The balance of this paper focusses mainly on using modelling to provide probabilistic estimates for the extent of coastal erosion hazard (comprising both long term trends and short term variability).

Emerging initially from New South Wales and Queensland State agencies, the discrimination of mean trend (e.g. recession) from fluctuating components (erosion and recovery) of shoreline location and their analysis can be summarised by the following:

$$d(t) = \bar{R}_V - \bar{R}_{SL} - E \qquad (1)$$

where

$d(t)$= distance from the present day scarp location at time t;
$\bar{R}_V$ = ongoing recession resulting from the time averaged sediment budget (+ve = accretion);
$\bar{R}_{SL}$= recession resulting from a rising sea level;
E = an allowance for storm erosion, representing movement of the shoreline from its pre-storm location to the base of the storm cut erosion scarp.

A further allowance can be made for post storm slumping and/or reduced foundation capacity [15] although, with adequate site investigation, this component can be treated deterministically and is set aside, for this paper, as we are using stochastic methods. With this in mind, it is clear that all three components on the right side of **Equation 1** are subject to significant uncertainty and we wish to address and incorporate an understanding of that uncertainty into our analyses.

3. Examining the Geomorphological Setting

In order to move beyond simplified rule of thumb assessments such as the Bruun Rule, it is important to gain a thorough grasp of the geomorphological history in response to the post glacial marine transgression and Holocene still-stand, and ongoing evolution of the shoreline including any trends that may have arisen from coastal works since European settlement.

Evolution of the coast is a complex outcome of changes over time. It continues to be constrained by subtle boundary conditions, such as the rate of supply of sediment, Such changes cannot be measured over short time scales, but may be deciphered through a combination of geomorphological studies with shorter term information, such as survey or modelling studies.

At Narrabeen Beach, a combination of data collected using ground penetrating radar (GPR) and a review of background geomorphological studies has informed our assessment. Outputs from a GPR survey along Albert Street are reproduced on **Figure 2**.

The GPR was interpreted temporally by utilizing pre-existing stratigraphic data from Narrabeen [21]. The rigour of the interpretation could be improved through dedicated sampling and optical stimulated luminescence dating along the profile.

Altogether, GPR records indicate that progradation of the barrier was punctuated by at least five major erosional events between 7,000 and 3,000 years BP. More research, including dating of samples from locations along the profile could be used to estimate recurrence intervals of these major events. Also detectable are a buried seawall and a major erosion scarp from the 1970's (the most seaward).

Geological [7, 8, 21] and historical [16, 17] evidence has been interpreted to gain quantitative understanding of different sediment budget components contributing to historical trends.

4. Assessing Long Term Trend Hazards

For long term trends, including those relating to present day sediment budget and those relating to sea-level rise, the Coastal Tract approach [3-5] and Shoreface Translation Model [i.e. STM, 3] were adopted.

At Narrabeen the approach utilised Monte Carlo techniques upon a single, laterally averaged cell spanning the coast between Long Reef to the south, and Turrimetta Headland to the north. The cell extended seawards to a depth of 100 metres.

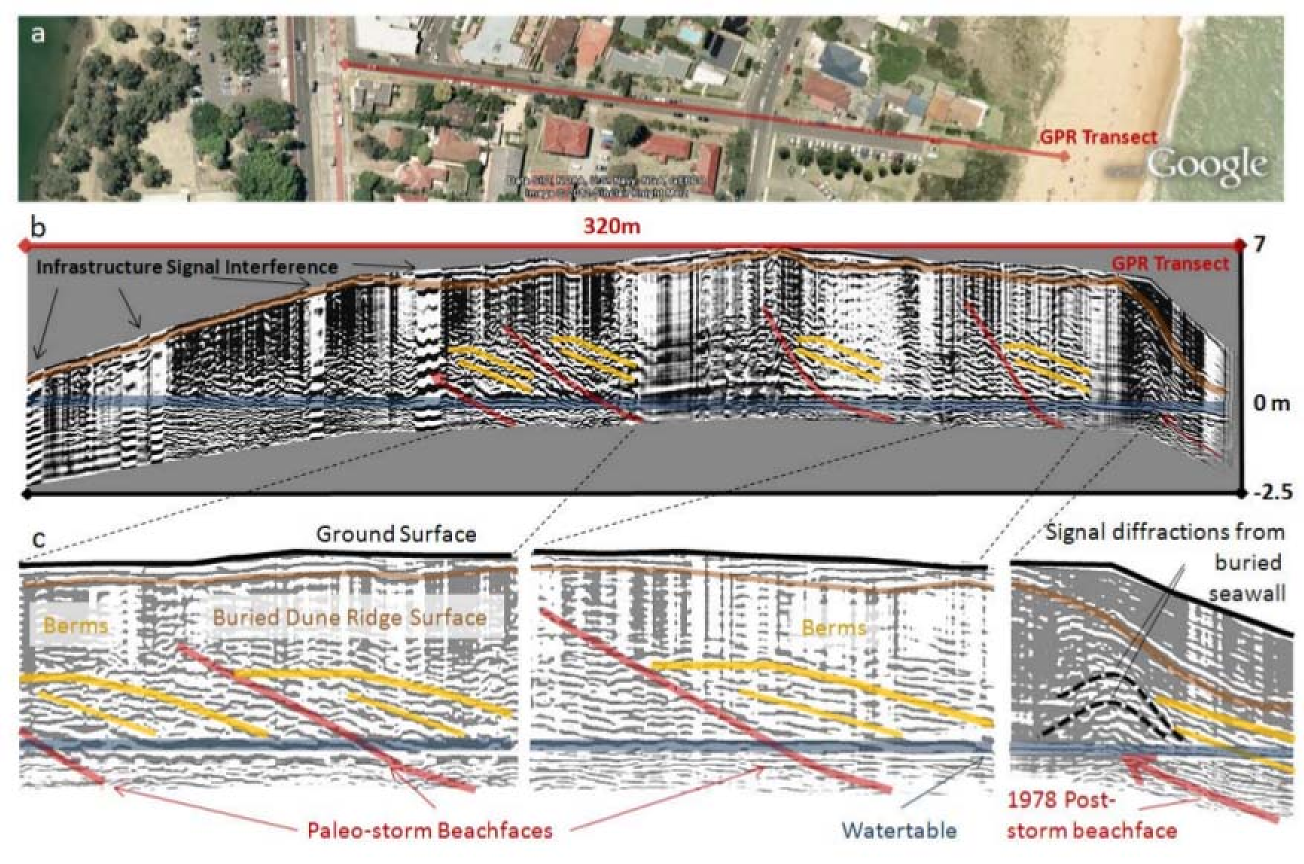

Figure 2: Representative GPR data from Narrabeen. The transect is from Albert St (a). The raw data from the entire transect line (b) shows 5 palaeo, post storm beach faces highlighted in red and subsequent accreted berms in yellow. The processed sections of the GPR (c) show these features in more detail, as well as those of the existing dune (brown) and a buried seawall (black)

Within the STM **Equation 2** is solved:

$$V_s - \int[h_t(x-R) - h_0(x) + S]dx = 0 \qquad (2)$$

where

V_s= gross sediment supply from outside the coastal cell summed across all cell boundaries
h_t, h_0 = alongshore averaged bed elevation at time t and t=0
R = shoreline recession distance
S = sea-level rise

Equation 2 is solved numerically to obtain quantitative estimates of the change in bathymetry over time. There are numerous uncertainties relating to (i) the amount of sea-level rise; (ii) the external sediment budget components; and (iii) the expected future cross-shore shape $h_t(x)$ which, importantly may not exhibit geometric similarity to the shape at *t=0*. Representation of the cross-shore profile is via a function with variable parameters, calibrated through alongshore averaging of terrain and bathymetric data, resulting in the generic geometry illustrated in **Figure 3.**

In general, there are seven components of long term sediment budget that may need to be considered: (i) littoral supply;(ii) in-situ production, especially biogenic carbonate; (iii) anthropogenic (e.g. sand mining, nourishment); (iv) beach/dune exchanges; (v) beach/tidal inlet exchanges; (vi) exchange with the continental shelf.

Monte Carlo analysis was used to incorporate key uncertainties into the resulting estimates of shoreline recession. To incorporate uncertainty suitable probability distributions for all input parameters were constructed.

In the case of estimates based on geological evidence, it is generally easier to identify feasible limits for various parameters, meaning that a triangular distribution, bounded by those limits is a simple and robust representation of probabilities.

It is possible to construct sea level rise trajectories using a normal probability density function [9, 10, 14]. However, given the common practice of IPCC reports to present ranges of likely sea-level rise, a triangular distribution can also be applied here.

For Narrabeen, the 1974 erosion scarp was adopted as a base reference line for movement. Preliminary Monte Carlo simulations were undertaken to fine tune the model over the historic period present from the photographic record (1941 – 1986).

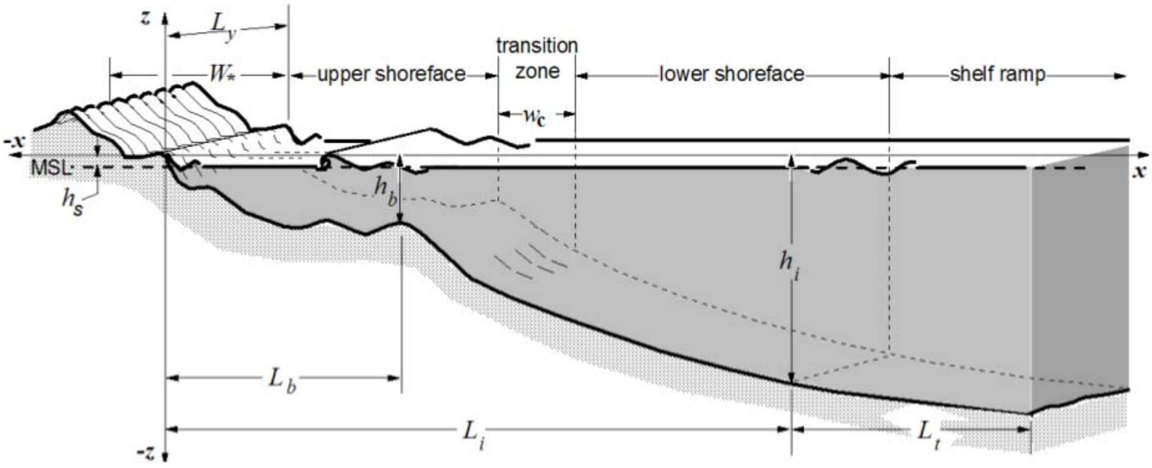

Figure 3: Cross shore parameters considered in constructing cross shore geometry. The cross shore profile of the inner continental shelf varies in time through constrained geometrical relationships containing a number of parameters. These parameters are assigned utilising sampling from imposed probability densities functions of their possible values.

These 'optimisation' trials involved fine tuning some of the parameters defining the lower shore geometry.

In defining the sediment budget various budget components were considered including the following:

1) There is a likely northward transport along the inner shelf, offshore from the prominent headlands, and this may represent a net loss of sand to the north of the Narrabeen embayment.

2) A possible range of $-10000 < V_s < 0$ m^3/m/yr sand loss was adopted, based on previous photogrammetric analyses[7, 16];

3) Based on the proportion of carbonate in the total late Holocene sand barrier, an estimate of the carbonate production rate was derived.

4) The rates of accumulation of the sediment volumes over time were assessed using ^{14}C dating and previous analyses (Roy and Lean, 1980). These analyses ultimately indicate that progradation of the Holocene barrier began around 7000 BP, but ceased at some stage between 3000 BP, with subsequent recession.

5) It is estimated that sand is lost to the Narrabeen Lagoon flood tide delta at a rate of 6,500 m^3/yr. Much of this sand is presently removed through a clearance operation and used to replenish the southern end of the beach.

6) The simulation needs to consider the possibility that eroded sand will be sequestered within accommodation space on the lower shelf, particularly under the effects of sea-level rise. The degree to which the lower shoreface dilates with rising sea level is also treated as uncertain, and modelled through adjustment of probability distributions, representing some parameters in **Figure 3**.

Use of the long term trend assessment results is presented and discussed in Section 6

5. Assessing Short Term Variability Hazards

Sandy beaches are inherently dynamic, undergoing gradual changes in response to incident waves and tidal variations. The most apparent changes occur as a result of increased wave energy during a storm event or a series of storms.

Storms erode the beach causing flattened beach profiles, erosional dune scarps, and wash-over deposits. During storms, sand is transported offshore forming near shore bars, which in most instances are later reworked back onshore by lower-energy swell waves after the storm event.

Post-storm recovery of the sub aerial beach face has been well documented [12], although the rate of recovery can vary substantially from beach to beach.

At Narrabeen, the model of [1] was adopted, with previous analyses presented for a central profile at Narrabeen Beach expanded to include five profiles along the entire beach. The model incorporates analysis of five variables: (i) Storm Duration (D); (ii) Peak Significant Wave Height (H); (iii) Storm maximum tidal anomaly (R); (iv) Significant Storm Wave Period (T); (v) Wave Direction (Dir); and Interstorm period (dt).

Generalised Pareto distributions were fitted to H, D and R and Logistics joint probability distributions between H&D (relatively strong) and H&R (relatively weak). T is related to H via a five parameter log normal distribution and wave direction is empirically distributed, based on measured storm data. Storm inter arrival time is assumed to be a Poisson process, with an expected arrival frequency that varies annually.

The model developed by [1] was based on the analysis of available storm data from Sydney. A site specific analysis would be required to justify appropriate interrelationships and probability distributions at other sites, but it is suggested that similar relationships to those described above may apply to similarly sited beaches. Some variation is expected to result from differences in the weather conditions that cause storms along any given coast.

The statistical model enables rapid sampling of realistic storm / inter-storm sequences. For planning periods of 110 years (1990- 2100), which would commonly be applied to sea level rise simulations, the sampling can be repeated thousands of times, for Monte Carlo analysis. The resulting progression of storm and inter-storm arrival periods enable simulation of storm erosion and subsequent recovery sequences (**Figure 4**).

Sometimes, recovery can be incomplete. A significant point regarding this method is it doesn't rely on a "design" storm specification. The "design" storm concept is problematic from a sandy coastline erosion perspective, as multiple storms may have the same effect as a single large storm. The effect of antecedence on beach condition is very important, as demonstrated by the 1974 events, a sequence of storms that is often used as a benchmark for design in New South Wales.

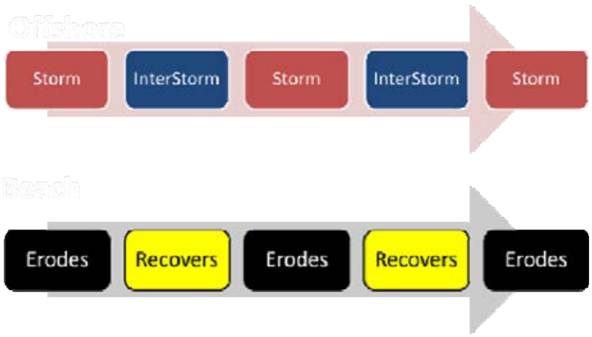

Figure 4: Representation of sampled storm and inter storm arrival periods as a sequence in time. Storms and inter-storm periods are sampled stochastically using the model of [1]

Nevertheless, specification of the beach recovery rate is also difficult, and does require the availability of suitable site specific data to estimate the rate of that process. In the case of Narrabeen, an exponentially decreasing recovery rate was determined, based on the findings of [18].

For calculating erosion, the time series of storm waves was converted to equivalent conditions at 20 m water depth (i.e. outside the surf zone) using pre-calculated wave transformation tables from the wave model SWAN [2], and surf zone transformations using linear wave theory and assuming parallel contours.

Subsequently, the dune erosion model of [13] was applied to determine erosion volumes. Briefly, that model relates the volume of eroded sand to the impact force caused by bores running up the beach and striking the eroding dune face. Geometrical relationships are then adopted to transfer eroded volume to a line at the top of the eroding scarp. The location of that scarp as it erodes and accretes is tracked during simulations and the results of many simulations can thereafter be analysed statistically to provide quantitative estimates for the risk assessment. The most landward scarp location in each simulated year was recorded for use in subsequent statistical analyses.

6. Combining the Hazards

Probability distributions were derived for both the long term and short term hazards. These were superposed via the convolution operation shown as Equation 3. The concept is demonstrated visually in **Figure 5**.

$$(f \times g)(x) = \int_{\infty}^{\infty} f(x-\tau) \times g(x) d\tau \qquad (3)$$

where
x = scarp location relative to present
$f(x)$= probability density function (pdf) of setback due to short term hazard;
$g(x)$= pdf of set back due to long term hazard;
$(f \times g)(x) =$ pdf resulting from convolution of $f(x)$ and $g(x)$.

The operation is repeated for a number of profiles along the beach, and a series of longshore aligned percentage exceedance curves constructed. By acquiring spatial data on values within areas landward of the beach, further analysis in GIS software or similar can then assign percentage exceedances to overall damage values. This last step is one of many ways that the *consequences* side of risk can be addressed.

7. Conclusions, Limitations and Subsequent Use

The developed framework formalises commonly applied coastal hazard analysis concepts, extending them for stochastic application.

The types of models available and computational capacity to undertake such assessments will improve over time. The models used here were necessarily simplified for our study to make them computationally tractable [23].

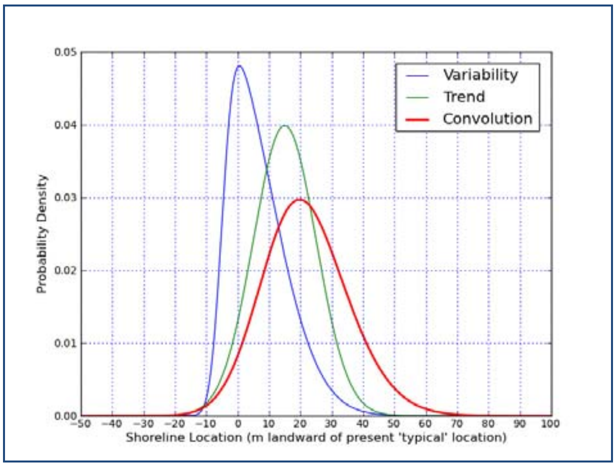

Figure 5: Combination of Long term and short term hazards. 'Trend' refers to long term hazard and 'variability' to the short term hazard.

Regardless, the adoption of a range of estimates of different probabilities is considered a more honest and transparent means of communicating the uncertainty with which coastal engineers and scientists view coastal processes and hazards, particularly when projecting future scenarios.

8. Acknowledgements

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